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A Modified Approach to Controller Partitioning

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ABSTRACT

The idea of computing a decentralized control law for the integrated flight/propulsion control of an aircraft by partitioning a given centralized controller is investigated. An existing controller partitioning methodology is described, and a modified approach is proposed with the objective of simplifying the associated controller approximation problem. Under the existing approach, the decentralized control structure is a variable in the partitioning process; by contrast, the modified approach assumes that the structure is fixed *a priori*. Hence, the centralized controller design may take the decentralized control structure into account. Specifically, the centralized controller may be designed to include all the same inputs and outputs as the decentralized controller; then, the two controllers may be compared directly, simplifying the partitioning process considerably.

Following the modified approach, a centralized controller is designed for an example aircraft model. The design includes all the inputs and outputs to be used in a specified decentralized control structure. However, it is shown that the resulting centralized controller is not well suited for approximation by a decentralized controller of the given structure. The results indicate that it is not practical in general to cast the controller partitioning problem as a direct controller approximation problem.

1. INTRODUCTION

1.1. The idea of integrated flight/propulsion control

Integrated flight/propulsion control (IFPC) is the name given to aircraft control design or action that accounts for the airframe and engine together as one integrated system [1]. An integrated control approach is required in cases where there is significant two-way coupling between the airframe and engine subsystems, making separate subsystem control designs inadequate for overall aircraft control. Such is the case for high-maneuverability aircraft, where airframe variables such as angle of attack and sideslip can have a significant effect on the engine dynamics. The general form of an integrated flight/propulsion control system is shown in Fig. 1.

From a theoretical standpoint, the notion of using a *centralized* controller for IFPC, such as that depicted in Fig. 1, is a natural one. However, practical requirements of implementation or validation may dictate that a *decentralized* control structure be used, with separate "subcontrollers" for the engine and the airframe [2]. Certain specified coupling, characterizing a well-defined interface, could be allowed between the subcontrollers. Given a particular decentralized control structure, the IFPC design task consists of choosing the parameters of the subcontrollers to obtain the desired characteristics of the overall closed-loop system.

1.2. IMPAC — an IFPC methodology

A methodology named IMPAC — an Integrated Methodology for Propulsion and Airframe Control — has recently been developed for decentralized IFPC design [3]. A flowchart of IMPAC is shown in Fig. 2. A key component of IMPAC is the use of "controller partitioning" for the design of decentralized flight/propulsion control laws. The essential elements of the controller partitioning methodology are (1) the design of a linear centralized controller (Fig. 2, block 2), and (2) the actual partitioning of the centralized controller to the desired decentralized structure by solving an appropriate approximation problem (Fig. 2, block 3). These elements are the focus of all the work described herein.

The decentralized control structure used under IMPAC is shown in Fig. 3. In the figure, the vectors z_a and z_e represent controlled variables of the airframe and engine subsystems, while z_{ac} and z_{ec} represent the respective command inputs for these variables. Thus, e_a and e_e represent tracking errors to be minimized. The controlled variables may be chosen according to the specific control objectives, but typically include airframe attitudes and rates for z_a , and particular engine temperatures, pressures, and turbine speeds for z_e . The vectors y_a and y_e represent any additional airframe and engine quantities assumed available for feedback, which may include the regulated

variables themselves. The airframe control inputs u_a , generated by the airframe subcontroller K^a , typically include the actuators for the airframe control surfaces, as well as thrust-vectoring angles for any vectorable nozzles. The engine control inputs u_e , generated by the engine subcontroller K^e , typically include the actuators for the nozzle areas and the fuel-flow rate.

The IMPAC control law includes unidirectional coupling between the subcontrollers, which effectively establishes a hierarchy between the subcontrollers, with the airframe subcontroller K^a on top. In addition to applying the inputs to the airframe control effectors, K^a generates thrust commands z_{eac} for the engine subsystem. The engine subcontroller K^e must ensure that the propulsion system supplies appropriate thrusts as commanded by K^a . One of the integrated control design requirements, therefore, is that the engine subsystem provide a certain bandwidth of thrust-command tracking. Implicit in such a requirement is the notion that the interface between the two subcontrollers must be a thrust command vector, and that K^e must treat the corresponding inputs e_{ea} as thrust errors to be minimized in the frequency range of interest. For purposes of analysis, the thrust vector z_{ea} is assumed to be available for feedback; in practice it would consist of estimates based on available measurements.

1.3. Controller partitioning under IMPAC

The first step of the controller partitioning effort under IMPAC is the design of a "global controller," which is a centralized controller that provides the standard for optimum performance and robustness of the closed-loop system. The requirements include independent tracking of command inputs by certain system outputs, up to a specified bandwidth, and robustness with respect to high-frequency multiplicative plant uncertainties at the outputs. The global controller can be computed via any suitable multivariable control synthesis technique, such as H_∞ or LQG/LTR. Examples of global IFPC designs are given in [4] and [5]. The control system including the global controller is shown in Fig. 4. Note that no thrust feedback is used. The absence of thrust feedback by the global controller turns out to be a key issue in the partitioning process.

The next step in the controller partitioning process is to define a "cost of partitioning," which has the form

$$J_{perf} = \|(K_g - K_{asm})W\|, \quad (1)$$

where the transfer function matrix $K_g(s)$ represents the global controller, $K_{asm}(s)$ represents the equivalent centralized controller obtained by combining the decentralized controllers in such a way that $K_{asm}(s)$ has the same inputs and outputs as $K_g(s)$, and $W(s)$ represents a chosen frequency weighting; $\|\cdot\|$ denotes a suitable norm. The cost J_{perf} is meant to reflect the match between the

overall performance and robustness of the decentralized controller and those of the centralized (global) controller.

Recall that one of the IFPC requirements under IMPAC is that the propulsion subsystem provide a certain bandwidth of thrust-command tracking. The cost of partitioning (1) does not reflect this requirement; therefore, an additional term is included in the cost. The total cost then has the form

$$J = J_{perf} + \lambda J_{track}, \quad (2)$$

where J_{perf} is given in (1) and J_{track} is the norm of a transfer function matrix constructed to represent the subsystem tracking performance [6]. The scalar weighting λ determines the relative weighting of the two components of the cost. This paper does not consider the subsystem tracking requirement; therefore, J_{track} is not discussed further.

To compute the cost (1) or (2) requires a direct comparison of the global and assembled controllers; that is, K_g and K_{asm} must have the same inputs and outputs. However, the decentralized controller of Fig. 3 uses additional measurements — the thrust variables z_{ea} — that the global controller omits. In order to compare the effects of the two controllers in the closed-loop system, the following device is used [6,7]: The dynamics of the integrated plant are introduced into the decentralized controller description, and the thrust feedback loop is closed; then, the effective transfer function matrix from the remaining controller inputs to the controller outputs can be determined. The resulting transfer-function matrix K_{asm} is shown in Fig. 5. Note that including the plant and the thrust feedback in K_{asm} is analogous to analyzing an open-loop system transfer-function matrix with an inner loop closed.

The final steps in controller partitioning are the parameterization of the decentralized controller and the optimization of the cost (2) over the feasible set of parameters. The initial parameters for the optimization are determined by a combination of methods: One block of the decentralized controller is initialized by an engine subsystem thrust-command tracking control design, with the design specifications derived from the closed-loop system thrust responses with the global controller; another is a lead filter with parameters initialized in an *ad hoc* way to compensate for the expected deficiency in the tracking bandwidth of the engine subsystem; the remaining blocks are initialized as low-order approximations of corresponding blocks of the global controller or of the centralized (global) closed-loop system [8]. Once the initial parameters are obtained, they are optimized by use of special-purpose numerical optimization software developed for this problem [6].

The controller partitioning methodology under IMPAC has been applied to two linear (single operating point) aircraft models — a short-takeoff-and-landing (STOL) model [4,7] and a short-takeoff-vertical-landing (STOVL) model [5,8,6]. The results have been promising: In each case, the centralized (global) controller provides the desired performance and robustness, and serves as a suitable standard for comparison. The initial parameterization process yields a reasonable decentralized controller, and the numerical optimization software succeeds in reducing the defined cost. In the optimization process, the designer can trade off overall system performance against the tracking bandwidth of the engine subsystem. The optimized decentralized controllers provide closed-loop system responses close to those obtained with the global controllers.

1.4. Issues to be considered

Although the experience with controller partitioning under IMPAC has been reasonably successful, the partitioning process has proved to be quite complicated. The cost function evaluation necessary at each iteration of the numerical optimization requires norm calculations for two high-order transfer function matrices. The associated gradient calculations, also required at each iteration, are likewise computationally demanding. Hence, there is reason to look for a means of simplifying the controller partitioning process.

An important complicating factor in the parameter optimization is a certain degree of incompatibility between the centralized (global) controller used and the decentralized control structure required. For example, $K_g(s)$ has a measurement structure different from that of the decentralized controller; as a result, the plant dynamics must be included in the assembled controller $K_{asm}(s)$, which increases the order of the transfer function constructed in the cost of partitioning (1). Also, the global controller design cannot accommodate the engine subsystem tracking specification; as a result, the J_{track} term is included in the cost (2), which approximately doubles the complexity of the cost function and gradient computations. Therefore, significant simplification of the controller partitioning process could result if the centralized and decentralized controllers could be made more compatible.

This report documents a modified approach to controller partitioning. The modification is intended to make the partitioning process simpler and more intuitively appealing. The idea is to make the centralized and decentralized control laws sufficiently compatible that the controller partitioning problem becomes a direct controller approximation problem. The following sections describe the modified partitioning methodology, and the specific advantages sought thereby; the general results of applying the methodology to an example problem; and a discussion and summary of the results.

2. A MODIFIED CONTROLLER PARTITIONING METHODOLOGY

2.1. Centralized design with thrust feedback

The basis for modifying the controller partitioning process is the redesign of the centralized controller to include the same measurements that the decentralized controller will ultimately include. For the case in question, the only difference in the centralized controller design would be the inclusion of the thrust measurements. The closed-loop system with the redesigned centralized controller K_c is shown in Fig. 6. The comparison of this centralized controller with the decentralized controller of Fig. 3 is direct.

Note that this change, while relatively modest, does nevertheless imply a modification of IMPAC. Specifically, the decentralized control structure must be determined before the centralized controller is designed. In Fig. 2, the modification implies that the centralized control design (block 2), in addition to the partitioning itself (block 3), would depend on the partitioned control structure.

The transfer-function matrix of the centralized controller K_c can be decomposed as

$$K_c = \begin{pmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \end{pmatrix}, \quad (3)$$

where the submatrices have dimensions that conform with the relation

$$\begin{pmatrix} u_a \\ u_e \end{pmatrix} = \begin{pmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \end{pmatrix} \begin{pmatrix} e_a \\ y_a \\ e_e \\ y_e \\ z_{ea} \end{pmatrix}, \quad (4)$$

with z_{ea} being the vector of thrust measurements. To make a block-by-block comparison of K_c with the decentralized controller, decompose the subcontrollers K^a and K^e as

$$K^a = \begin{pmatrix} K_1^a \\ K_2^a \end{pmatrix}, \quad K^e = [K_1^e \quad K_2^e], \quad (5)$$

where the submatrices conform with the relations

$$u_a = K_1^a \begin{pmatrix} e_a \\ y_a \end{pmatrix}, \quad z_{eac} = K_2^a \begin{pmatrix} e_a \\ y_a \end{pmatrix}, \quad u_e = [K_1^e \quad K_2^e] \begin{pmatrix} e_e \\ y_e \\ z_{eac} - z_{ea} \end{pmatrix}. \quad (6)$$

The overall decentralized controller transfer-function matrix, for comparison with (3), is now determined by some simple algebra as

$$K_d = \begin{pmatrix} K_1^a & 0 & 0 \\ K_2^e K_2^a & K_1^e & -K_2^e \end{pmatrix}. \quad (7)$$

Since the centralized controller (3) and the decentralized controller (7) may now be directly compared, the cost of partitioning can be expressed as a norm of the weighted difference between the two controllers; that is,

$$J_{perf} = \|(K_c - K_d)W\|, \quad (8)$$

where $W(s)$ is an appropriate frequency weighting. Thus, the cost of partitioning is that associated with a direct controller approximation problem.

This investigation concentrates on the effect of the modified centralized control structure on the optimization of J_{perf} . The issue of subsystem thrust-command tracking is not considered. In effect, the scalar parameter λ in (2) is taken to be zero, so that J_{track} is omitted from the cost; J_{perf} is defined by (8). The motivation for omitting J_{track} from the investigation was to simplify the parameter optimization process, and to determine whether the J_{perf} optimization, which had seemed to be ill-posed under the IMPAC approach, would be well-posed under the modified approach.

2.2. The initial partitioning

The direct comparison that can now be made between the centralized and decentralized controllers allows a simple computation of the initial decentralized controller parameters. The basis for determining the initial parameters is the approximation of certain blocks of the centralized controller by the corresponding blocks of the decentralized controller. Such approximations could be made with or without any frequency weightings. For simplicity, frequency weightings are omitted from this discussion of initial partitioning; they could easily be added, with some complication of the approximation processes involved. Specifically, the decentralized controller parameters can be chosen such that

$$K_1^a \approx K_{11}, \quad (9)$$

$$K_1^e \approx K_{22}, \quad (10)$$

$$K_2^e \approx -K_{23}, \quad (11)$$

and

$$K_2^e K_2^a \approx K_{21}. \quad (12)$$

Of course, it is not possible to directly approximate the centralized controller blocks K_{12} and K_{13} with the given decentralized control structure; therefore, these blocks must not be essential to the centralized controller performance if the approximation process is to be successful.

The subcontroller block K_1^a can be determined as a reduced-order model of K_{11} . Any model-order reduction technique, such as the method of internally balanced realization [9], could be used. The whole engine subcontroller $K^e = [K_1^e \ K_2^e]$ can be determined as a reduced-order model of $[K_{22} \ -K_{23}]$; this is preferable to computing separate approximations of K_1^e and K_2^e , which is bound to result in a combined realization of much higher order. Thus, the approximations (9), (10), and (11) can be accomplished using only two model-order reductions of submatrices of the K_c .

The approximation (12) is slightly more complicated: Given that K_2^e is already fixed, (12) boils down to a form of the model-matching problem

$$\min \{ \|K_{21} - K_2^e K_2^a\| : K_2^a \text{ proper, stable} \}. \quad (13)$$

The model-matching problem can be easily transformed into an optimal control synthesis problem. Fig. 7 shows a block diagram of the expression $K_{21} - K_2^e K_2^a$ rearranged in the form of a standard generic feedback control system. (This rearrangement is given in [10].) Here, the blocks K_2^e and K_{21} are elements of the generalized control design plant, and K_2^a is the feedback controller to be designed. If the norm assumed in (13) is, for example, the H_2 norm or the H_∞ norm, then the optimal approximation can be determined by solving the algebraic Riccati equations associated with the equivalent optimal control synthesis problem; see [11]. The order of the optimal K_2^a will be the sum of the orders of K_2^e and K_{21} ; model-order reduction can then be applied to K_2^a to compute a lower-order (suboptimal) solution.

If K_2^e is close to $-K_{23}$, as in (11), the model-matching problem (13) is almost the same as the alternative model-matching problem

$$\min \{ \|K_{21} + K_{23} K_2^a\| : K_2^a \text{ proper, stable} \}. \quad (14)$$

When this alternative model-matching problem is transformed to an equivalent optimal control synthesis problem, the generalized control design plant consists of the blocks K_{21} and K_{23} . These blocks are derived from a single transfer function matrix; therefore, the design plant composed of

these two blocks has the order of either one of these blocks, not the sum of the orders of the two. Hence, the optimal solution K_2^a of (14) is of lower order than the solution of (13). The order of K_2^a can, of course, be further reduced by model-order reduction techniques.

2.3. The parameter optimization

The remaining task is to adjust the parameters of the blocks of the decentralized controller to optimize the cost function (8). The direct comparison between the centralized and decentralized controllers allows the parameter optimization problem, although still quite complicated, to be as simple as possible. Procedures for carrying out the numerical parameter optimization are discussed in [6] and [7].

3. APPLICATION OF THE MODIFIED METHODOLOGY TO AN EXAMPLE

3.1. The example considered

The modified controller partitioning methodology was applied to a control design problem previously addressed using the IMPAC methodology, namely a linear plant model representing the longitudinal airframe dynamics and engine dynamics of an E-7D STOVL aircraft traveling at 80 knots in decelerating transition to hover [5]. The plant included four airframe control inputs and four engine control inputs. The overall plant model was of 18th order, including 4th-order longitudinal airframe dynamics, 6th-order engine dynamics, and first-order actuator dynamics at each of the eight control inputs. The objective of the control system design was to guarantee decoupled command tracking for three airframe outputs and one engine output. In addition to the tracking errors, there were five airframe quantities and one engine quantity assumed available for feedback. The z_{ea} variables were three thrusts, associated with three engine exhaust nozzles; it was these three thrusts that were to track airframe-generated thrust commands in the decentralized IMPAC design. Although in practice these thrusts would have to be estimated, they were assumed in the analysis to be directly available for feedback in both the centralized and decentralized designs.

3.2. The centralized controller design results

The H_∞ control design method [11] was used for designing the centralized controller. This method consists basically of optimizing a cost function defined in terms of the transfer functions of the closed-loop system. The transfer functions considered have the externally supplied command signals and the measurement noises as inputs, and the tracking errors as outputs; see Fig. 8. The various inputs and outputs are given weightings in the cost function corresponding to their relative importance in the design. These weightings, which may be frequency-dependent, constitute the design parameters in the cost function that are adjusted to reflect the performance and robustness specifications. For example, increasing the weighting on a particular measurement noise would indicate that the corresponding measurement should be assumed more noisy, or that the design should be more robust with respect to perturbations in that measurement. For this problem, the weightings were chosen (for the most part) to be the same as those determined to be suitable for the global control design in the IMPAC study [5]. Including all the weightings, the design plant was of order 29; hence, the H_∞ control synthesis yielded a controller that was also of order 29. The controller contained seven "fast" modes that were eliminated by modal residualization, leaving a centralized controller of order 22.

The centralized H_∞ design was successful, in the sense that it provided overall system performance that satisfied all the design specifications. As an example of the system performance, Fig. 9 compares the closed-loop responses to a step-input velocity command using the modified centralized controller K_c with those using the IMPAC global controller K_g . The figure shows that the responses were similar. There was, however, a notable peculiarity to the design: The magnitude of the thrust feedback was extremely sensitive to the weighting of the thrust-measurement noises in the H_∞ cost function. Fig. 10 shows the singular values of the blocks K_{ij} of the centralized controller K_c , as defined by (3), for two cases: Fig. 10(a) shows the case where all the measurement noises are given equal weightings; Fig. 10(b) shows the case where the thrust-measurement noises are weighted by 20 dB less than the other measurement noises. The curves marked K_{13} and K_{23} represent the thrust-feedback frequency responses of the controller. The figures show that, when equal weighting was given to all the measurements, the thrust measurement was barely used by the controller, but a 20-dB decrease in the thrust-measurement noise weightings relative to the other noise weightings caused a 40-dB increase in the thrust feedback. This apparent trend also held as the thrust-measurement noise weightings were further decreased.

Stranger still, the system step responses and frequency responses were unaffected by the choice of the thrust-measurement noise weightings. That is, both of the controllers characterized in Fig. 10, as well as other controllers computed using different weightings, resulted in closed-loop systems having practically identical performance. The drastic differences in thrust-feedback magnitude were ultimately irrelevant to the control system performance. Naturally, the control systems with more thrust feedback had smaller stability margins with respect to perturbations in the thrust-feedback loops. In the end, the basis for choosing the thrust-measurement noise weightings was to obtain a thrust feedback of roughly the same order of magnitude as the feedback of the other plant measurements. Thus, the controller depicted in Fig. 10(b) was chosen to be used for the rest of the study. This choice also gave reasonable stability margins in the thrust-feedback loops.

3.3. The initial partitioning results

The initial decentralized controller parameters were determined by separate approximations of the various blocks of the centralized controller. A 12th-order realization for K_1^a and an 11th-order realization for K^e were obtained by the method of internally-balanced model-order reduction from the 22nd-order realizations of K_{11} and $[K_{22} \ K_{23}]$, respectively. These approximations were quite accurate. However, the optimal solution K_2^a of the model-matching problem defined by Equation (14) resulted in a crude approximation $-K_{23}K_2^a$ of the block K_{21} . At some frequencies, the relative magnitude of the error, as given by the expression

$$E(\omega) = \frac{\sigma_{\max}\{K_{21}(j\omega) + K_{23}(j\omega)K_2^a(j\omega)\}}{\sigma_{\max}\{K_{21}(j\omega)\}},$$

was as much as 55%. (Fig. 11 shows a plot of $E(\omega)$ over frequency.) This substantial discrepancy occurred even though the model-matching solution K_2^a was optimal for the problem as formulated. The trouble was that, with K_{23} fixed, the choice of K_2^a allowed insufficient freedom to make the product $-K_{23}K_2^a$ an accurate approximant of K_{21} . In essence, the columns of $K_{21}(j\omega)$ were outside the range space of $K_{23}(j\omega)$. As a result, the initial decentralized controller K_d was not an accurate approximant of the centralized controller K_c . In fact, K_d did not even provide closed-loop stability for the system.

4. DISCUSSION

The main goal of the modified approach to controller partitioning has been to make the centralized controller more amenable to approximation by a decentralized controller of a given structure. To what extent has this goal been achieved? It is true that the centralized and decentralized controllers have been given the same input/output structure; however, the two controllers use the available measurements in a completely different way. Most notably, the optimal centralized controller does not need the thrust measurements: It barely uses them unless the design assumes they are practically noise-free by comparison with the other available measurements. Further, the performance of the centralized closed-loop system does not depend on the thrust feedback. It would seem most logical to omit the thrust measurements altogether from the centralized controller design. By contrast, the decentralized controller must use the thrust measurements: Even setting aside the requirement of thrust-command tracking, the thrust feedback by the engine subcontroller is tied to the coupling from the airframe subcontroller, and therefore cannot be eliminated without completely decoupling the engine controls from the airframe measurements. Thus, the results of the centralized design suggest that the centralized and decentralized control structures considered here are fundamentally incompatible. That is, given the assumed decentralized control structure, the goal of expressing the controller partitioning problem as a direct controller approximation problem may be impossible to achieve.

The main impediment to the success of the modified controller partitioning approach is the particular hierarchical decentralized control structure assumed. If controller partitioning is to be cast as the direct approximation of a given optimal centralized controller by a decentralized controller, then the decentralized control structure must be compatible with the characteristics of the centralized controller. The optimal centralized design should serve to guide the selection of the decentralized control structure. That is, according to the importance of the various coupling (off-diagonal) elements of the centralized controller transfer-function matrix, certain measurements should be made available to both the engine subcontroller and the airframe subcontroller. The shared measurements should be few enough that the interface between the controllers is relatively simple, so that a procedure for independent validation of the subcontrollers could be formulated.

On a conceptual level, the nature of the controller partitioning process depends on the assumed relationship between the centralized control design and the decentralized control structure. Under the IMPAC methodology, the centralized controller and the decentralized control structure are independent; the partitioning process is complicated and somewhat unnatural, because it must accommodate the two, no matter how they are chosen. Under the modified approach, the centralized controller is designed according to the given decentralized control structure; the

partitioning process is simplified to a direct controller approximation. Although this is intuitively appealing, the approximation problem may not have a satisfactory solution. Under a third approach, not yet considered, the decentralized control structure would be chosen according to the characteristics of the optimal centralized controller; again, the partitioning process would become a direct controller approximation. The intuitive appeal of the modified approach would be retained, and a satisfactory decentralized approximant could likely be found, because the centralized and decentralized control structures would be compatible by design.

There are, of course, other approaches to simplifying the decentralized IFPC design process. It should be noted that the indirect controller partitioning approach under IMPAC yields reasonable decentralized IFPC designs, and that a fine-tuning of the IMPAC approach could result in some simplification. An alternative approach would be to design the decentralized control law by the direct optimization of the decentralized closed-loop system; under this approach, the selection of both the decentralized control structure and the cost function to be optimized could be guided by an optimal centralized control design for the system. The computations involved in the direct optimization could be less demanding than those required for controller partitioning.

5. SUMMARY

The objective of this study has been to make the process of controller partitioning simpler and more natural by treating it as a direct controller approximation problem. The approach has been to redesign the centralized controller to include the thrust measurements that are to be used by the decentralized control law. The result is that the centralized and decentralized controllers may be compared directly, so that the approximation problem is clearly and naturally defined; however, the centralized controller handles the thrust measurements in such a way that the decentralized approximation cannot be made accurate. Thus, the assumed decentralized control structure precludes the formulation of a direct controller approximation problem for controller partitioning. Any significant simplification of the decentralized IFPC design process will require either a different decentralized control structure, or a design approach other than controller partitioning.

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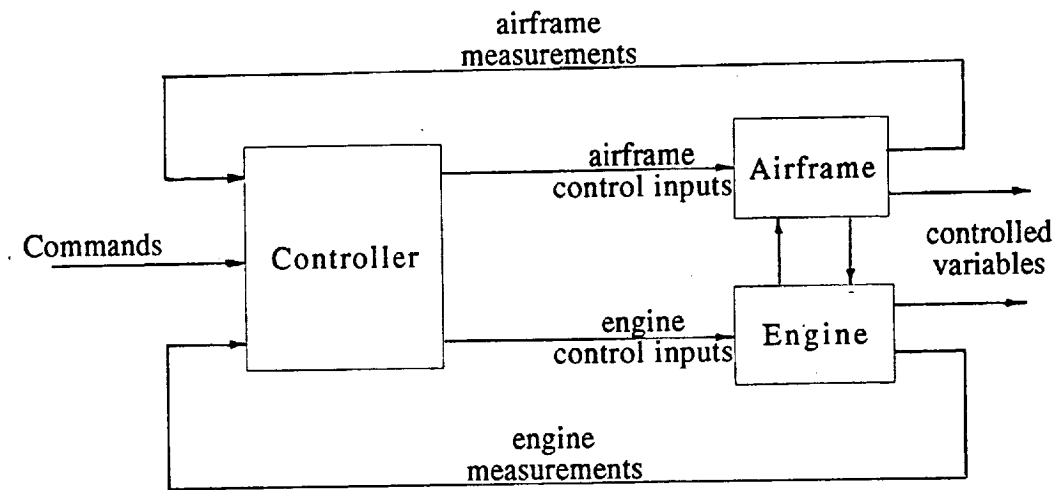


Figure 1. The general form of an integrated flight/propulsion control system.

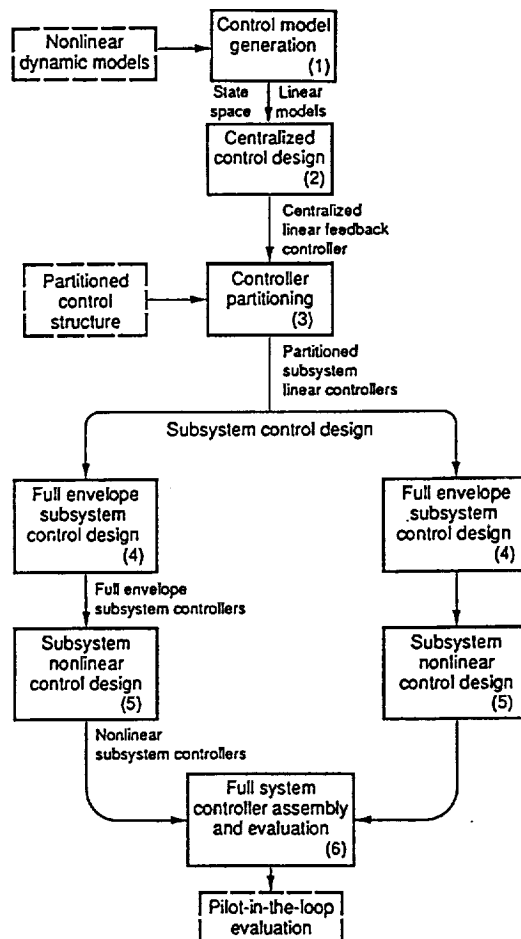


Figure 2. The IMPAC flowchart.

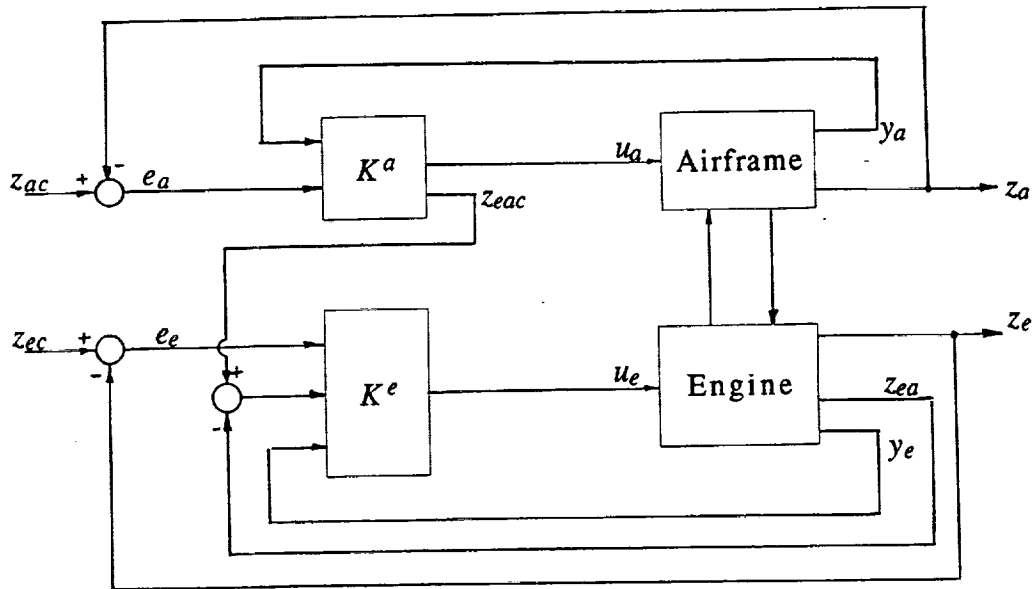


Figure 3. The decentralized control structure used under IMPAC.

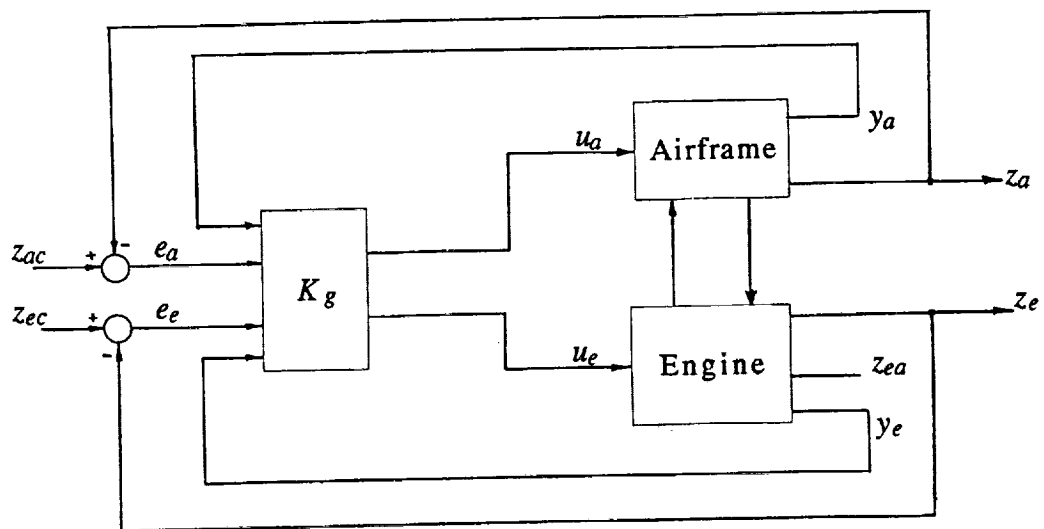


Figure 4. The closed-loop system with the IMPAC global controller.

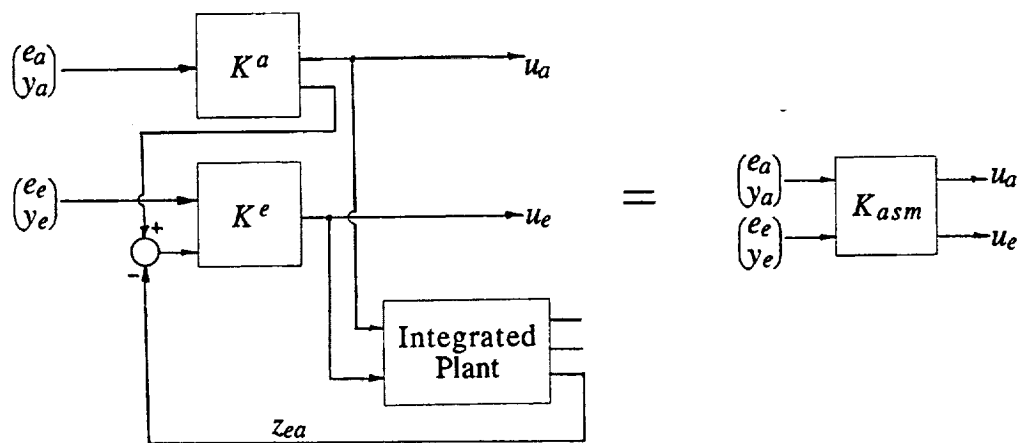


Figure 5. Construction of the equivalent assembled controller.

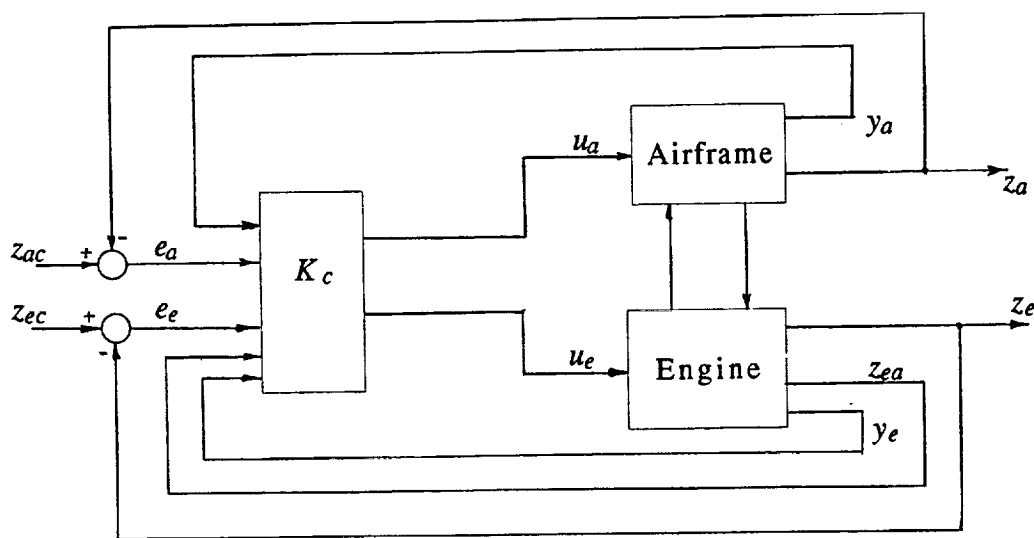


Figure 6. The closed-loop system with the modified centralized controller.

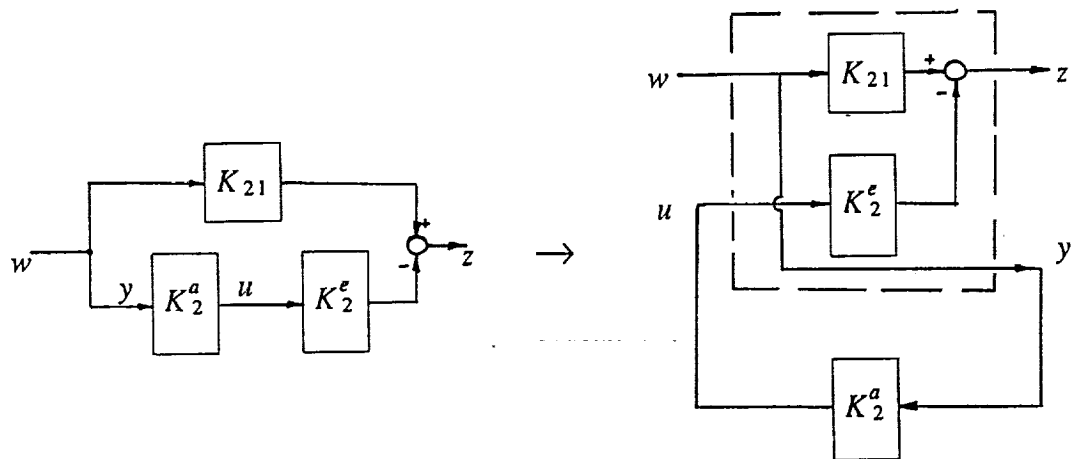


Figure 7. Transforming the model-matching problem into a generic control problem.

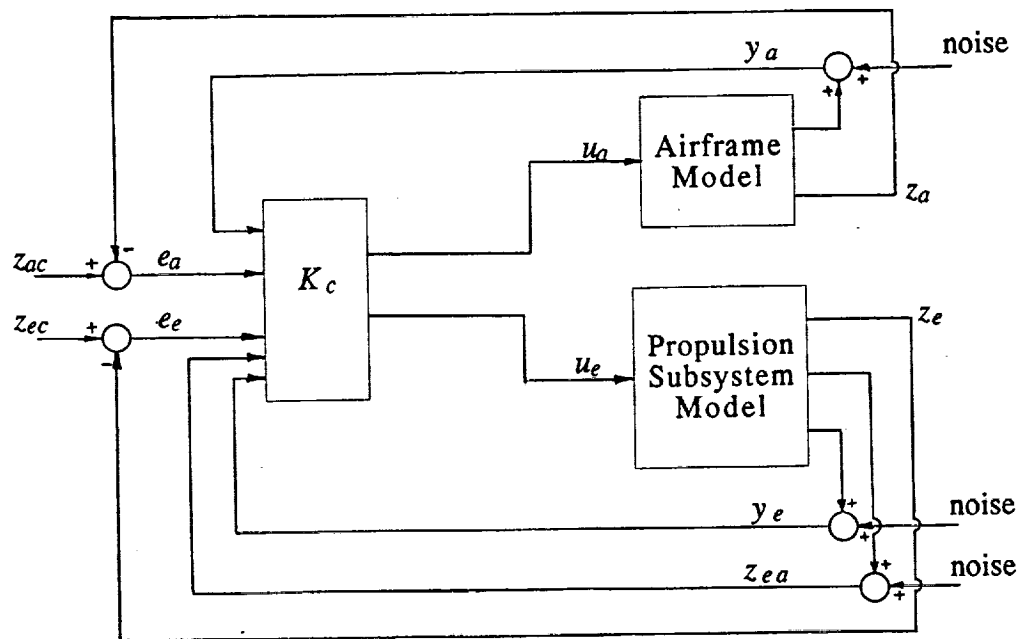
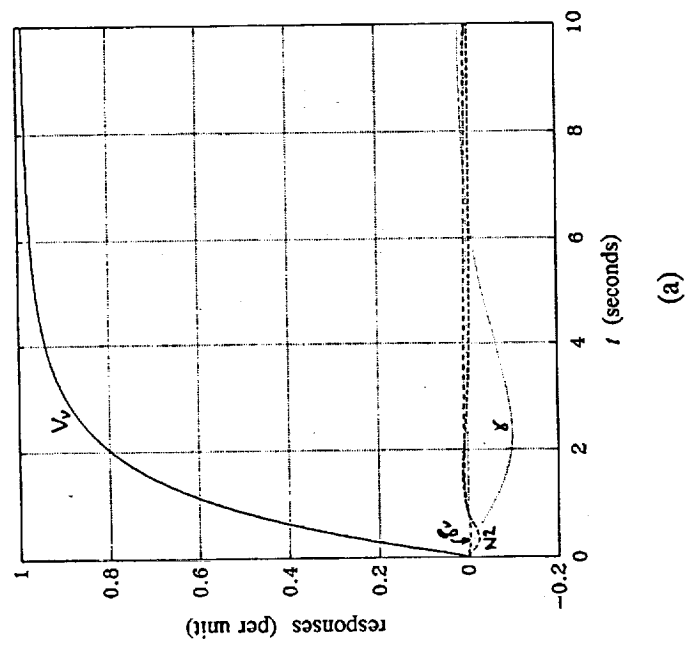
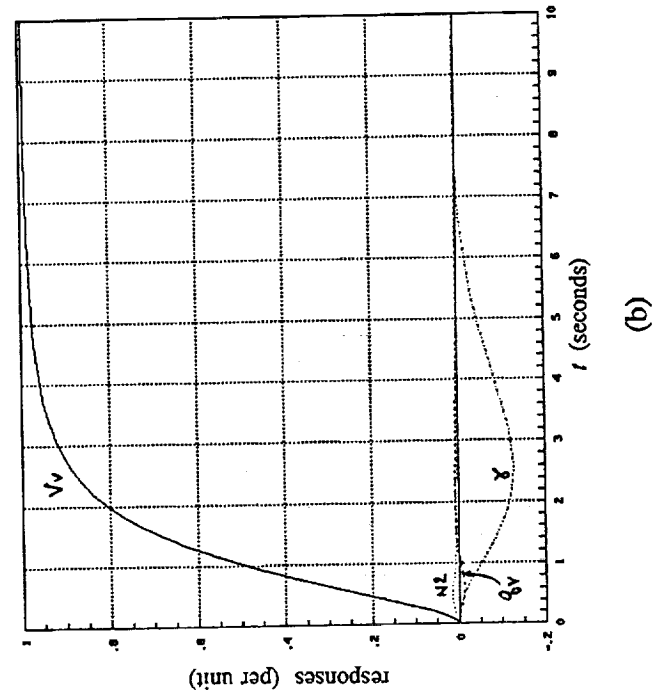


Figure 8. Block diagram for centralized control design.



(a)



(b)

Figure 9. Responses to a step-input velocity command.
 (V_v = velocity, N_2 = fan speed, q_v = pitch rate, γ = flight-path angle.)
 (a) IMPAC global controller, (b) Modified centralized controller.

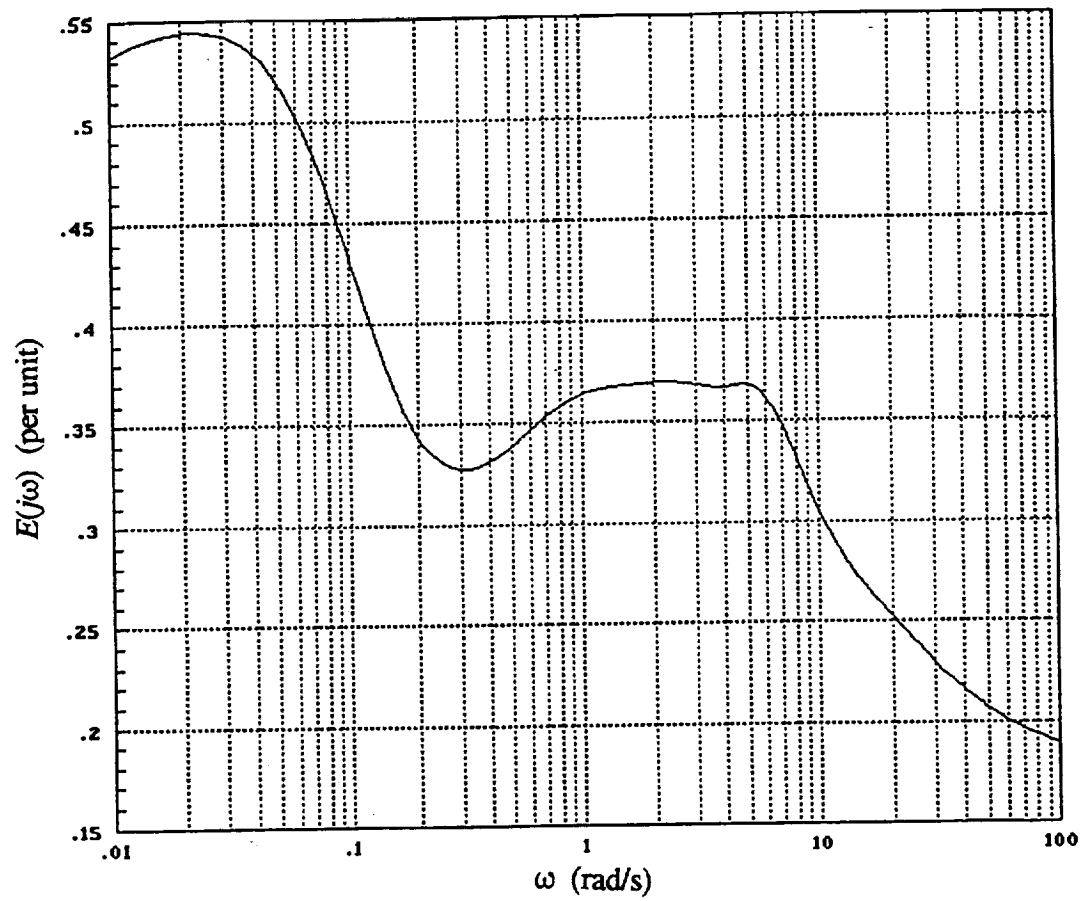


Figure 11. Relative error in the optimal model-matching approximant.

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13. ABSTRACT (Maximum 200 words) The idea of computing a decentralized control law for the integrated flight/propulsion control of an aircraft by partitioning a given centralized controller is investigated. An existing controller partitioning methodology is described, and a modified approach is proposed with the objective of simplifying the associated controller approximation problem. Under the existing approach, the decentralized control structure is a variable in the partitioning process; by contrast, the modified approach assumes that the structure is fixed <i>a priori</i> . Hence, the centralized controller design may take the decentralized control structure into account. Specifically, the centralized controller may be designed to include all the same inputs and outputs as the decentralized controller; then, the two controllers may be compared directly, simplifying the partitioning process considerably. Following the modified approach, a centralized controller is designed for an example aircraft model. The design includes all the inputs and outputs to be used in a specified decentralized control structure. However, it is shown that the resulting centralized controller is not well suited for approximation by a decentralized controller of the given structure. The results indicate that it is not practical in general to cast the controller partitioning problem as a direct controller approximation problem.				
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